# 1 Introduction

Cyclic loadings on a structural component occur because of changes in mechanical and thermal loadings as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to any other load set. For each load set, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the lifetime of the component to the allowable cycles. Figures I–9.1 through I–9.6 of Appendix I to Section III of the ASME Boiler and Pressure Vessel Code specify fatigue design curves that define the allowable number of cycles as a function of applied stress amplitude. The cumulative usage factor (CUF) is the sum of the individual usage factors, and the ASME Code Section III requires that the CUF at each location must not exceed 1.

The ASME Code fatigue design curves, given in Appendix I of Section III, are based on strain–controlled tests of small polished specimens at room temperature in air. The design curves have been developed from the best–fit curves to the experimental fatigue–strain–vs.–life (ε–N) data that are expressed in terms of the Langer equation[1] of the form

$$\varepsilon_a = A1(N)^{-n1} + A2, \tag{1}$$

where $\varepsilon_a$ is the applied strain amplitude, N is the fatigue life, and A1, A2, and n1 are coefficients of the model. Equation 1 may be written in terms of stress amplitude $S_a$ instead of $\varepsilon_a$, in which case stress amplitude is the product of $\varepsilon_a$ and elastic modulus E, i.e., $S_a = E\,\varepsilon_a$. The fatigue design curves were obtained from the best–fit curves by first adjusting for the effects of mean stress on fatigue life and then reducing the fatigue life at each point on the adjusted curve by a factor of 2 on strain (or stress) or 20 on cycles, whichever is more conservative.

The factors of 2 and 20 are not safety margins but rather conversion factors that must be applied to the experimental data to obtain reasonable estimates of the lives of actual reactor components. Although the Section III criteria document[2] states that these factors were intended to cover such effects as environment, size effect, and scatter of data, Subsection NB–3121 of Section III of the Code explicitly notes that the data used to develop the fatigue design curves (Figs. I–9.1 through I–9.6 of Appendix I to Section III) did not include tests in the presence of corrosive environments that might accelerate fatigue failure. Article B–2131 in Appendix B to Section III states that the owner's design specifications should provide information about any reduction to fatigue design curves that has been necessitated by environmental conditions.

The existing fatigue ε–N data illustrate potentially significant effects of light water reactor (LWR) coolant environments on the fatigue resistance of carbon and low–alloy steels,[3–5] as well as of austenitic stainless steels (SSs).[4–7] Under certain environmental and loading conditions, fatigue lives of austenitic SSs can be a factor of 20 lower in water than in air.[6]

In LWR environments, the fatigue lives of austenitic SSs depend on applied strain amplitude, strain rate, temperature, and dissolved oxygen (DO) in water. A minimum threshold strain is required for environmentally assisted decrease in the fatigue life.[7] Environmental effects on life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Strain rate and temperature have a strong effect on fatigue life in LWR environments.[6,7] Fatigue life decreases logarithmically with decreasing strain rate below 0.4%/s; the effect saturates at 0.0004%/s. Similarly, the fatigue ε–N data suggest a threshold temperature of 150°C; in the range of 150–325°C, the logarithm of life decreases linearly with temperature. The effect of DO on fatigue life may depend on the composition and heat treatment of the steel. Limited data indicate that, in high–DO water, the magnitude of environmental effects is influenced by material heat treatment.[7] In low–DO water, material heat treatment seems to have little or no effect on the fatigue life of austenitic SSs.

Two approaches have been proposed for incorporating the environmental effects into ASME Section III fatigue evaluations for primary pressure boundary components in operating nuclear power plants: (a) develop new fatigue design curves for LWR applications, or (b) use an environmental correction factor to account for the effects of the coolant environment. In the first approach, following the same procedures used to develop the current fatigue design curves of the ASME Code, environmentally adjusted fatigue design curves are developed from fits to experimental data obtained in LWR environments. Interim fatigue design curves that address environmental effects on the fatigue life of carbon and low–alloy steels and austenitic SSs were first proposed by Majumdar et al.[8] Fatigue design curves based on a more rigorous statistical analysis of experimental data were developed by Keisler et al.[9] These design curves have subsequently been updated on the basis of updated statistical models.[4,5]

The second approach, proposed by Higuchi and Iida,[10] considers the effects of reactor coolant environments on fatigue life in terms of an environmental correction factor $F_{en}$, which is the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into fatigue evaluations, the fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the environmental correction factor. Specific expressions for $F_{en}$, based on the Argonne National Laboratory (ANL) statistical models[4,5] and on the correlations proposed by the Ministry of International Trade and Industry (MITI) of Japan,[11] have been proposed.

This report presents experimental data on the effect of heat treatment on fatigue crack initiation in austenitic Type 304 SS in LWR coolant environments. A detailed metallographic examination of fatigue test specimens was performed to characterize the crack morphology and fracture morphology in austenitic SSs in air, and boiling water reactor (BWR) and pressurized water reactor (PWR) environments. The key material, loading, and environmental parameters and their effect on the fatigue life of these steels are also described. Statistical models are presented for estimating the fatigue ε–N curves for austenitic SSs as a function of material, loading, and environmental parameters. The two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented.

# 6 Incorporating Environmental Effects into Fatigue Evaluations

The effects of LWR coolant environments may be incorporated into the ASME Section III fatigue evaluations by either developing a new set of environmentally adjusted fatigue design curves or by using a fatigue life correction factor $F_{en}$ to adjust the current ASME Code fatigue usage values for environmental effects. For both approaches, the magnitude of key loading and environmental parameters that influence fatigue life must be known. Estimates of fatigue life based on the two approaches may differ because of differences between the ASME mean curves used to develop the current design curves and the best–fit curves to the existing data that are used to develop the environmentally adjusted curves. However, either method provides an acceptable approach to account for environmental effects.

## 6.1 Fatigue Design Curves

A set of environmentally adjusted fatigue design curves may be developed from the best–fit of stress–vs.–life curves to the experimental data in LWR environments by following the procedure that was used to develop the current ASME Code fatigue design curves. The stress–vs.–life curve is obtained from the ε–N curve, e.g., stress amplitude is the product of strain amplitude and elastic modulus. The best–fit experimental curves are first adjusted for the effect of mean stress. As mentioned earlier the current ASME Code fatigue design curve for austenitic SSs does not include a mean stress correction below $10^6$ cycles because, for the current Code mean curve, the fatigue strength at $10^6$ cycles is greater than the monotonic yield strength of these steels. The best–fit curve in a specific environment is corrected for mean stress effects with the modified Goodman relationship given by:

$$S'_a = S_a\left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y, \tag{21}$$

and

$$S'_a = S_a \qquad \text{for } S_a > \sigma_y, \tag{22}$$

where $S'_a$ is the adjusted value of stress amplitude, and $\sigma_y$ and $\sigma_u$ are yield and ultimate strengths of the material, respectively. Equations 21 and 22 assume the maximum possible mean stress and typically give a conservative adjustment for mean stress, at least when environmental effects are not significant. The fatigue design curves are then obtained by lowering the adjusted best–fit curve by a factor of 2 on stress or 20 on cycles, whichever is more conservative, to account for differences and uncertainties in fatigue life that are associated with material and loading conditions. $S'_a$

For environmentally adjusted fatigue design curves, a minimum threshold strain is defined, below which environmental effects are insignificant. The Pressure Vessel Research Council steering committee for Cyclic Life Environmental Effects* has endorsed this threshold value and proposed a ramp for the threshold strain: a lower strain amplitude below which environmental effects are insignificant, a slightly higher strain amplitude above which environmental effects decrease fatigue life, and a ramp between the two values. The two strain amplitudes are 0.10 and 0.11% for austenitic SSs (both wrought and cast).

* Welding Research Council Progress Report, Vol. LIX No. 5/6, May/June 1999.

An example of fatigue design curves for austenitic SSs in LWR environments at 289°C is shown in Fig. 29. Because the fatigue life of Type 316NG is superior to that of Types 304 or 316 SS at high strain amplitudes, the design curves in Fig. 29 may be somewhat conservative for Type 316NG SS.

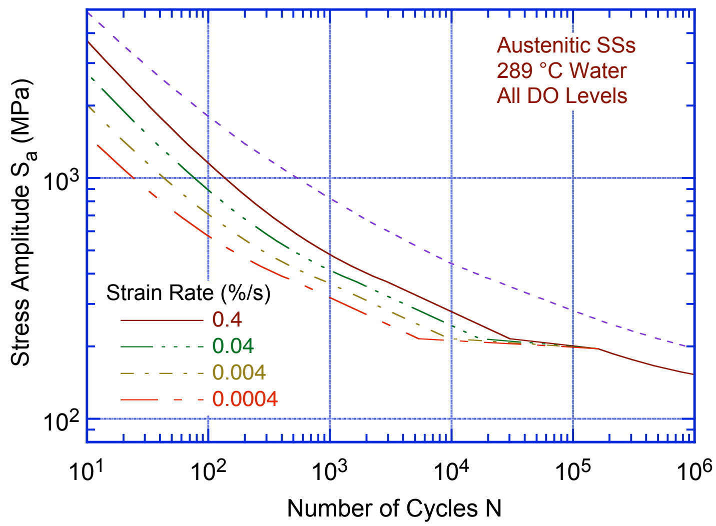


Figure 29. Fatigue design curves developed from statistical model for austenitic stainless steels in LWR environments at 289°C under service conditions where all threshold values are satisfied.

## 6.2 Fatigue Life Correction Factor

The effects of reactor coolant environments on fatigue life have also been expressed in terms of a fatigue life correction factor $F_{en}$, which is defined as the ratio of life in air at room temperature to that in water at the service temperature. Values of $F_{en}$ can be obtained from the statistical model, where:

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \tag{23}$$

The fatigue life correction factor for austenitic SSs, based on the ANL model, is given by

$$F_{en} = \exp(1.028 - T' \; \dot{\varepsilon}' \; O'), \tag{24}$$

where the constants T', $\dot{\varepsilon}'$, and O' are defined in Eqs. 8–10. $F_{en}$ based on the MITI guidelines is given in Eqs. 11–15. To incorporate environmental effects into a Section III fatigue evaluation, the fatigue usage for a specific stress cycle, based on the current Code fatigue design curve, is multiplied by the correction factor.

# 7 Summary

Fatigue tests have been conducted on two heats of Type 304 SS under various material conditions to determine the effect of heat treatment on fatigue crack initiation in these steels in air and LWR environments. A detailed metallographic examination of fatigue test specimens was performed, with special attention to crack morphology at the sites of initiation, the fracture surface, and the occurrence of striations.

The results indicate that heat treatment has little or no effect on the fatigue life of Type 304 SS in air and low–DO PWR environments. In a high–DO BWR environment, fatigue life is lower for sensitized SSs; life continues to decrease as the degree of sensitization is increased. The cyclic strain–hardening behavior of Type 304 SS under various heat treatment conditions is identical, only the fatigue life varies in different environments.

In air, irrespective of the degree of sensitization, the fracture mode for crack initiation (crack lengths up to ≈200 µm) and crack propagation (crack lengths >200 µm) is transgranular (TG), most likely along crystallographic planes, leaving behind relatively smooth facets. With increasing degree of sensitization, cleavage–like or stepped TG fracture, and occasionally ridge structures on the smooth surfaces were observed. In the BWR environment, the initial crack appeared intergranular (IG) for all heat–treatment conditions, implying a weakening of the grain boundaries. For all four conditions tested, the initial IG mode transformed within 200 µm into a TG mode with cleavage–like features. It appears, however, that the size of the IG portion of the crack surface increased with the degree of sensitization. By contrast, for all of the samples tested in PWR environments, the cracks initiated and propagated in a TG mode irrespective of the degree of sensitization. Prominent features of all fracture surfaces in the PWR case were highly angular, cleavage–like fracture facets that exhibited well–defined “river” patterns. Intergranular facets were rarely observed, but when they were found, it was mostly in the more heavily sensitized alloys.

Fatigue striations normal to the crack advance direction were clearly visible beyond ≈200 µm on the fracture surfaces for all material and environmental conditions. Striations were found on both the TG and IG facets of the samples tested in BWR conditions, or co-existing with the “river” patterns specific to the samples tested in the PWR environment. Evidence of extensive rubbing due to repeated contact between the two mating surfaces was also found.

The orientation of the cracks as they initiated at the specimen surface was also a function of the test environment. For air tests, cracks initiated obliquely, approaching 45°, with respect to the tensile axis. By contrast, for tests in either BWR or PWR environment cracks tended to initiate perpendicular to the tensile axis. In all environments, the overall orientation of the crack became perpendicular to the tensile axis as the crack grew beyond the initiation stage.

In air, the fatigue lives of Types 304 and 316 SS are comparable; those of Type 316NG are superior to those of Types 304 and 316 SS at high strain amplitudes. The fatigue lives of austenitic SSs in air are independent of temperature in the range from room temperature to 427°C. Also, variation in strain rate in the range of 0.4–0.008%/s has no effect on the fatigue lives of SSs at temperatures up to 400°C. The fatigue ε–N behavior of cast SSs is similar to that of wrought austenitic SSs.

Review of the available data show that the fatigue lives of cast and wrought austenitic SSs are decreased in LWR environments; the decrease depends on strain rate, DO level in water, and temperature.

A minimum threshold strain is required for environmentally assisted decrease in the fatigue life of SSs, and this strain appears to be independent of material type (weld or base metal) and temperature in the range of 250–325°C. Environmental effects on fatigue life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Strain rate and temperature have a strong effect on fatigue life in LWR environments. Fatigue life decreases logarithmically with decreasing strain rate below 0.4%/s. The effect saturates at 0.0004%/s. Similarly, the fatigue ε–N data suggest a threshold temperature of 150°C; in the range of 150–325°C, the logarithm of life decreases linearly with temperature.

The fatigue lives of wrought and cast austenitic SSs are decreased significantly in low–DO (i.e., <0.01 ppm DO) water. In these environments, the composition or heat treatment of the steel has little or no effect on fatigue life. However, in high–DO water the environmental effects on fatigue life are influenced by the composition and heat treatment of the steel. For a high–carbon heat of Type 304 SS, environmental effects were significant only for the sensitized steel. For a low–carbon heat of Type 316NG SS, some effect of environment was observed even for MA steel in high–DO water, although the effect was smaller than that observed in low–DO water. Limited fatigue ε–N data indicate that the fatigue lives of cast SSs are approximately the same in low– and high–DO water and are comparable to those observed for wrought SSs in low–DO water.

Statistical models for the fatigue life of austenitic SSs as a function of material, loading, and environmental parameters have been developed. The functional form of the model and bounding values of the important parameters are based on experimental observations and data trends. The models are recommended for predicted fatigue lives of $\leq 10^6$ cycles. Consistent with previous work by Jaske and O'Donnell, the present results indicate that even in air the ASME mean curve for SSs is not consistent with the experimental data. The ASME curve is nonconservative. The results that correspond to the 50th percentile of the statistical model are considered to be the best fit to the experimental data.

Two approaches are presented for incorporating the effects of LWR environments into ASME Section III fatigue evaluations**.** In the first approach, environmentally adjusted fatigue design curves are developed by adjusting the best–fit experimental curve for the effect of mean stress and by setting margins of 20 on cycles and 2 on strain to account for the uncertainties in life associated with material and loading conditions. These curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. The second approach considers the effects of reactor coolant environments on fatigue life in terms of an environmental correction factor $F_{en}$, which is the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into the ASME Code fatigue evaluations, a fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the correction factor.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

The ASME Boiler and Pressure Vessel Code provides rules for the design of Class 1 components of nuclear power plants. Figures I–9.1 through I–9.6 of Appendix I to Section III of the Code specify design curves for applicable structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. The existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of LWR coolant environments on the fatigue resistance of pressure vessel and piping steels. Under certain environmental and loading conditions, fatigue lives of austenitic stainless steels (SSs) can be a factor of 20 lower in water than in air. This report presents experimental data on the effect of heat treatment on fatigue crack initiation in austenitic Type 304 SS in LWR coolant environments. A detailed metallographic examination of fatigue test specimens was performed to characterize the crack morphology and fracture morphology. The key material, loading, and environmental parameters and their effect on the fatigue life of these steels are also described. Statistical models are presented for estimating the fatigue ε–N curves for austenitic SSs as a function of material, loading, and environmental parameters. Two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented.

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